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# $MgB_2$ RF Surface Resistance Dependence on Magnetic Fields

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# Participants in the Collaboration

- Los Alamos Neutron Science Center (LANSCE) at LANL: Tsuyoshi Tajima, Jianfei Liu, Alan Shapiro, Frank Krawczyk, Dale Schrage, Bill Clark, Rich Sheffield
- Superconductivity Technology Center (STC) at LANL: Alp Findikoglu, Fred Mueller
- Superconductor Technologies, Inc. (STI): Brian Moeckly
- University of California, San Diego (UCSD): Vitali Nesterenko and his group
- Cornell University: Alexander Romanenko, Hasan Padamsee

# Outline

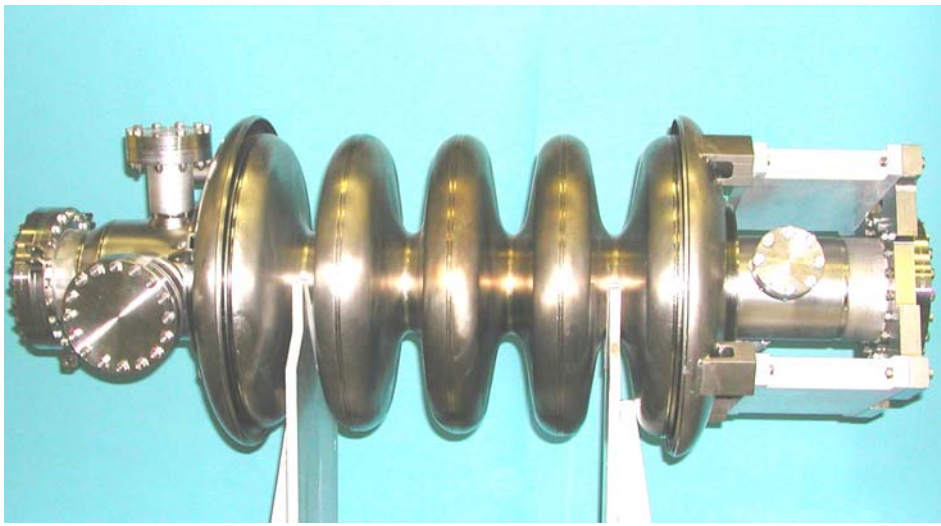
- Purpose of this study
- New tests results on $R_s$ under low magnetic fields
- Plans for $R_s$ measurements at high magnetic fields
- Some $R_s$ results at 6 GHz under relatively high magnetic fields up to ~120 Oe, which corresponds to an accelerating gradient of ~3 MV/m in electron particle accelerators.
- Summary and future plans

# Purpose

- Evaluate $MgB_2$ as a material for Superconducting RF (SRF) cavities for future particle accelerators.
  - Conventional Nb technology has been improved in the past decade to reach close to the theoretical limit (~2000 Oe, theory also needs to be re-visited)
  - Best 20< SRF cavities have shown 1750+-100 Oe
  - Without finding new materials that can exceed Nb theoretical limit, no more significant benefit from superconductivity is foreseen in the future.

    A Review talk of Nb SRF cavities by Hasan Padamsee at the Thursday Plenary Session

# An Example of SRF Cavity: APT $\beta$ = 0.64, 700 MHz, 5-Cell Cavity



Cavity length : 116 cm

Cell diameter : 40 cm

Beam aperture : 13 cm

$E_{pk}/E_{acc}$ : 3.38

$B_{pk}/E_{acc}$ : 6.96 mT/MV/m

# Theoretical limits

- Accelerating gradient
  - Fundamental limit is peak surface magnetic field, which leads to quench if exceeded.  Typical ratio of magnetic field (H) to accelerating gradient ($E_{acc}$) is $H/E_{acc}$~40 Oe/MV/m, i.e., ~2000 Oe means $E_{acc}$~50 MV/m.
- Cavity surface RF loss
  - It is measured by a cavity unloaded quality factor ($Q_0$) which is inversely proportional to the surface resistance $R_s$. ($Q=G/R_s$) where G is a structural constant called geometrical factor determined by the cavity shape.
  - BCS resistance ($R_{BCS}$) is the theoretical limit assuming residual loss is sufficiently low.

# Benefit of higher-$T_c$ materials

- Higher gradient??
  - Experimentally, no material has shown higher critical magnetic field than Nb so far. $MgB_2$ has not been tested yet. An old theory predicts higher critical field for some materials such as $Nb_3Sn$ than Nb, but this theory is inconsistent with experimental data.
  - Demonstrating critical magnetic field higher than Nb is imperative to show the benefit

# Benefit of higher-$T_c$ materials

- Lower loss?
  - Assuming the same level of residual loss with Nb, the theoretical limit is $R_{BCS}$

$$R_{BCS} = A \cdot \frac{f^2}{T} \exp\left( -\frac{\Delta}{k_B T_c} \cdot \frac{T_c}{T} \right)$$

Higher $T_c$ leads to lower $R_{BCS}$ at the same temperature if the energy gap ratio, $\Delta/k_B T_c$, is the same.

The benefit would be higher $Q_0$ at 4 K.

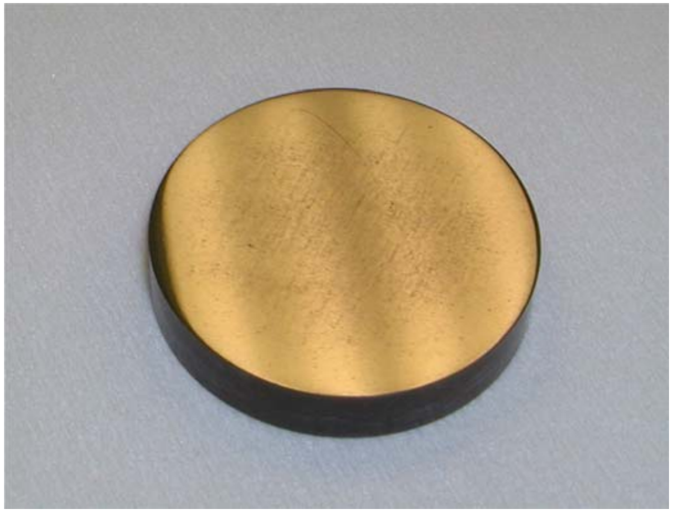
Currently, cavities of a frequency higher than ~500 MHz needs to be operated at <4K to reduce the cryogenic load, but it could be operated at 4 K with higher-$T_c$ cavities, that would reduce the construction and operation cost of cryogenic system.

# Magnesium diboride ($MgB_2$)

- It has been shown that the links between grains are strong compared to other high $T_c$ materials, which gives us hope.
- Collaborations with the following institutions
  - University of California, San Diego (UCSD), Vitali Nesterenko and his group for high-density bulk material using hot-isostatic press technique
  - Superconductor Technologies, Inc., Brian Moeckly for films on sapphire and metals
  - Measurements with Cornell University
- For high gradient applications, near-bulk property might be necessary based on Nb film on Cu cavity studies
- Films could be advantageous in terms of cost, thermal stability using a higher-thermal conductivity material as a substrate such as copper

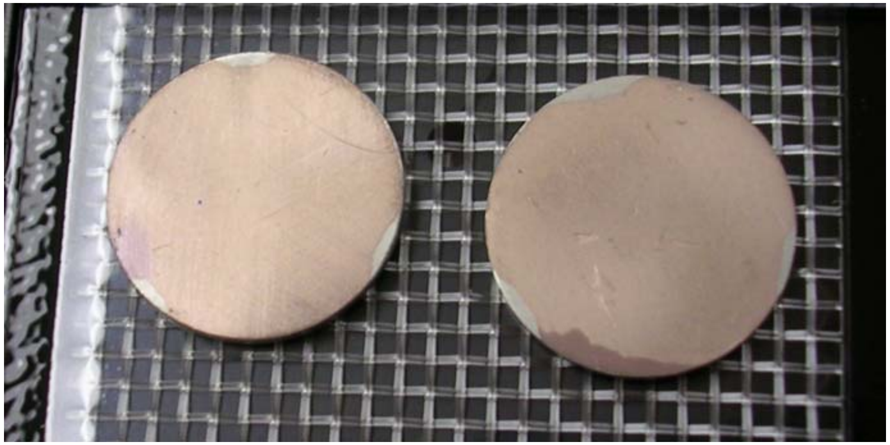
# Samples

Bulk sample made by HIP at UCSD



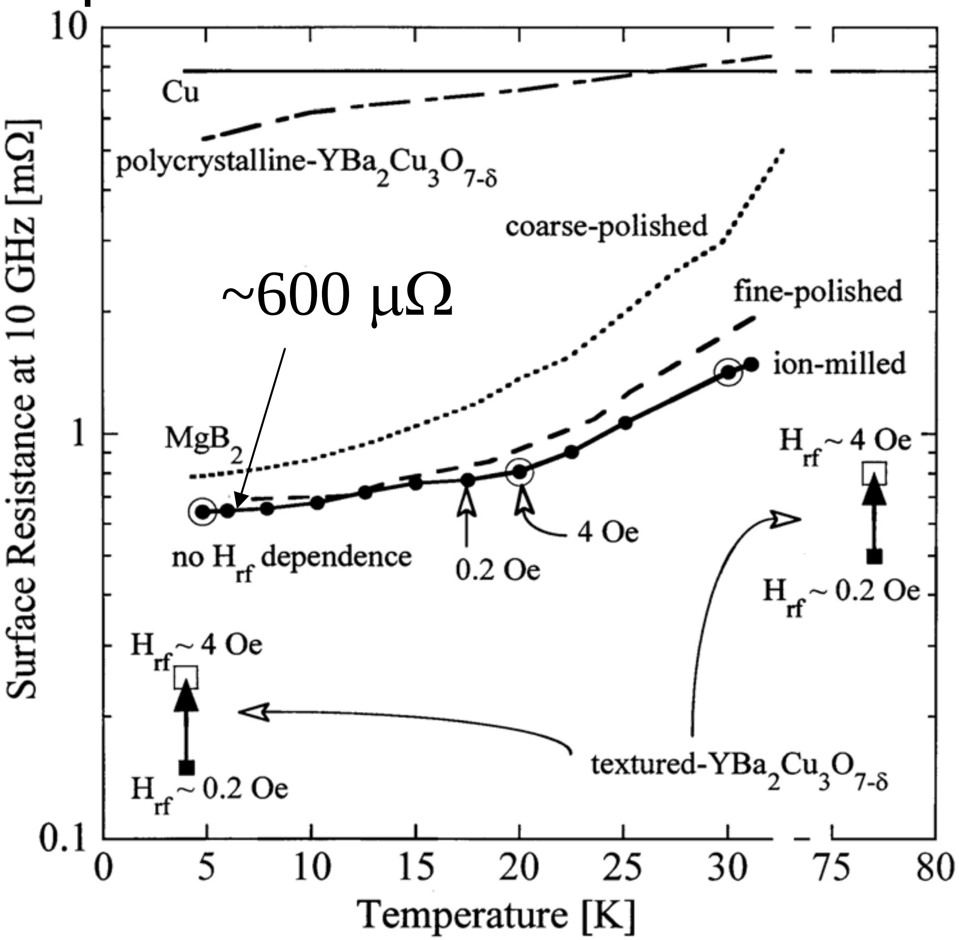
25.0 mm in diameter and 4.60 mm in thickness after polishing the surface with a $0.1-\mu m$ diamond lapping film.  A reflection of 3 fluorescent lights is seen on the surface.

400 nm film on Nb coated at STI



Diameter: 14.6 mm
Substrate: 1 mm Nb

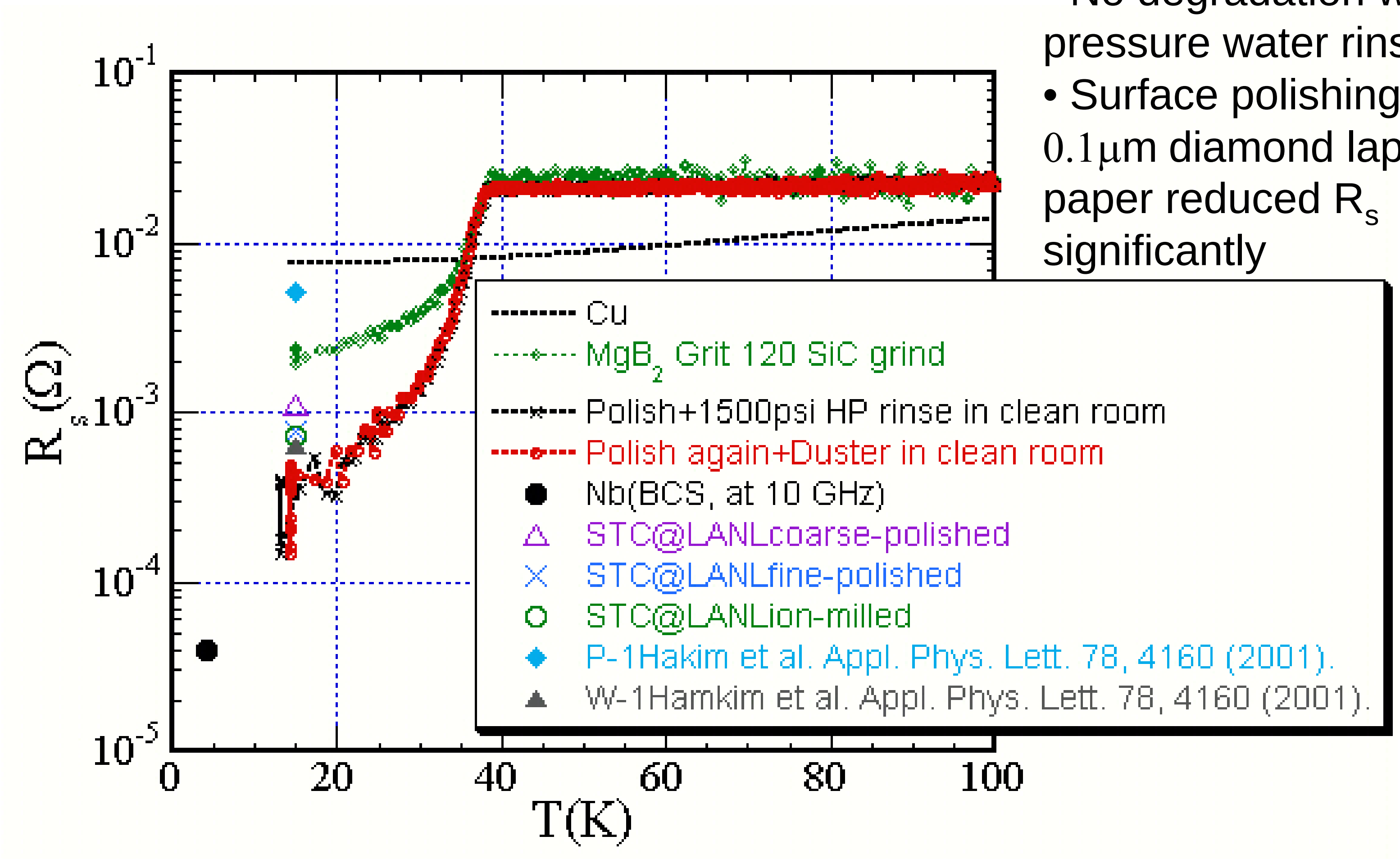
# First RF Surface Resistance Measurement of HIP Bulk Sample at STC of LANL




- No increase of $R_s$ from 0.2 to 4 Oe as compared to significant increase with YBCO.
- This material is not optimized for low $R_s$, i.e., there is room for improvement
- $R_s$ (BCS) of Nb (4K, 10 GHz) ~ 40 μΩ

Alp Findikoglu et al. (Superconductivity Technology Center at LANL), Applied Physics Letters 83 108 (2003).

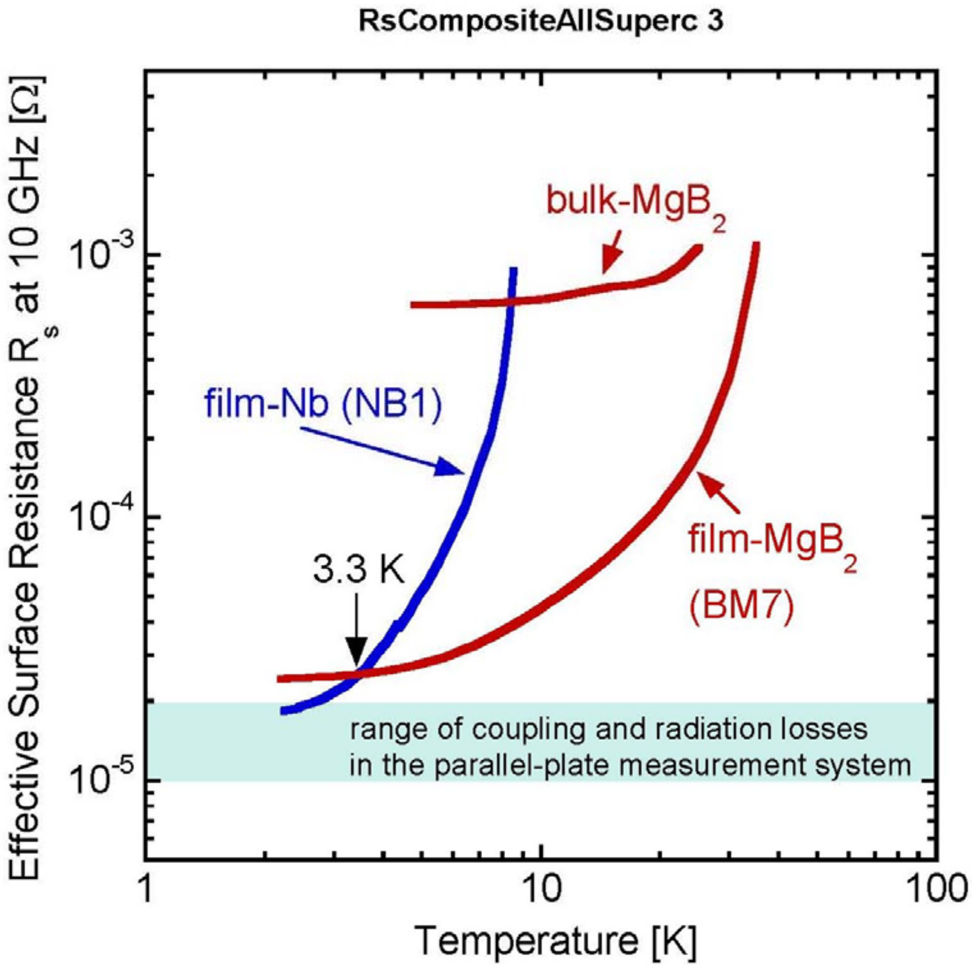
# RF Surface Resistance Measurement of HIP Bulk $MgB_2$ at LANSCE of LANL: Results Converted to 10 GHz




- No degradation with high-pressure water rinse
- Surface polishing with 0.1μm diamond lapping paper reduced $R_s$ significantly

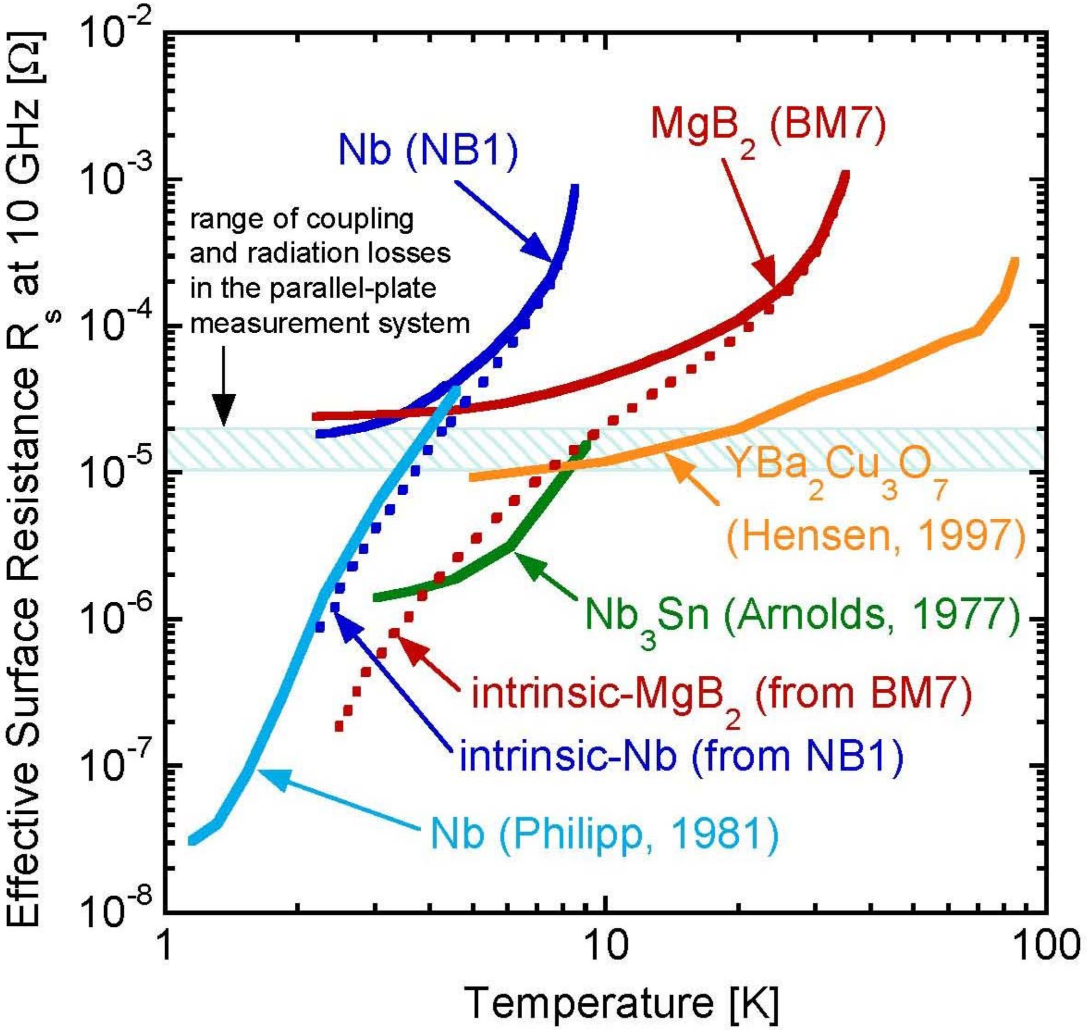
T. Tajima, J. Liu et al., 6th European Conference of Applied Superconductivity, Sorrento, September 14-18

# 400nm film on 1 $cm^2$ sapphire substrate showed further $R_s$ reduction, lower than Nb at 4 K!!




- Data taken by Alp Findikoglu of STC at LANL, unpublished
- Film prepared by Brian Moeckly of Superconductor Technologies, Inc.
- Polycrystal, non-epitaxial film

# Intrinsic (BCS) Resistance could be about one order of magnitude lower than Nb at 4 K!!




Alp Findikoglu of STC at LANL, unpublished

# An attempt to coat $MgB_2$ on metals such as Nb has started at STI

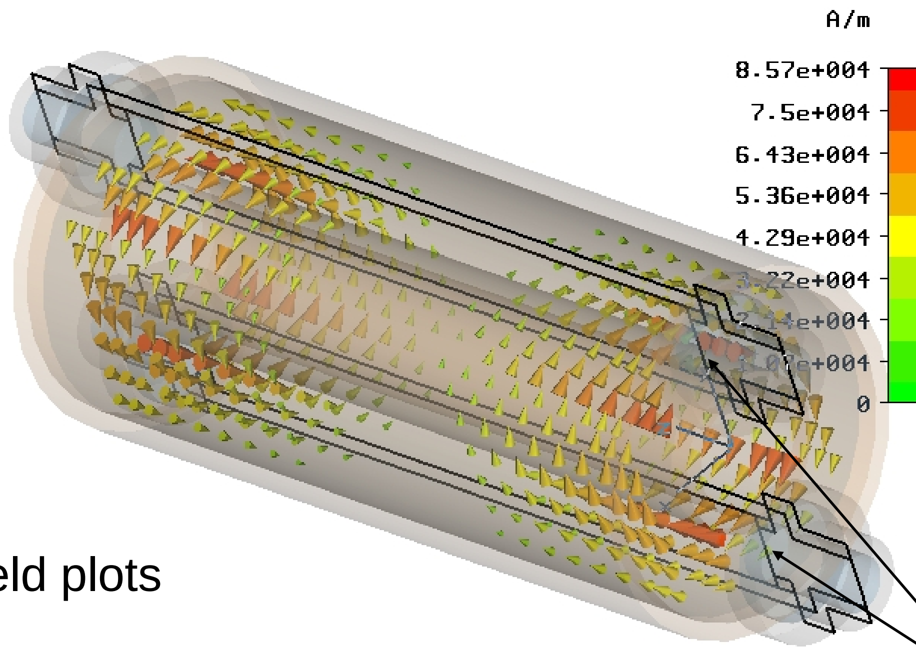
Talk of Moeckly at 4:00 PM on Thursday (4MS)

- Using the same technique on Sapphire, two 1.46 cm-diameter Nb disks (1 mm in thickness) were coated with $MgB_2$ by Brian Moeckly of STI.
- This is the first attempt and no optimization has been done yet.
- A parallel plate measurement was carried out by Alp Findikoglu of LANL. $R_s$ was about one order of magnitude higher than that coated on sapphire, but could be improved with better substrate surface preparation, etc.

# $R_s$ dependence on Magnetic Fields Measurements are Underway

- Tests with a ~760 MHz Nb coax cavity at LANSCE of LANL, no data yet
- Tests with a 6 GHz $TE_{011}$-mode cavity at Cornell University, some data in the next slides

# Tests at LANSCE using a 760-MHz Nb coaxial cavity, no data yet




Magnetic field plots

```
Type         = H-Field (peak)
Monitor      = Mode 1
Maximum-3d = 85745.5 A/m at 0.0211375 / 0.004305 / 0.2087
Frequency    = 701.178
Phase        = 90 degrees
```

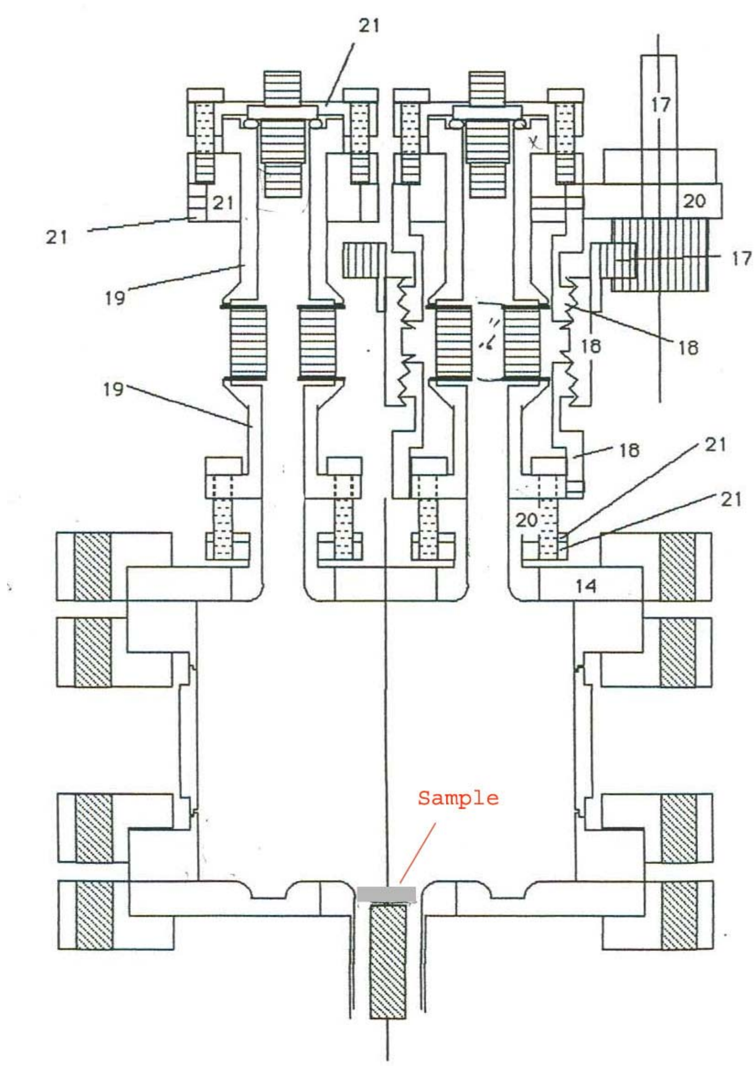
Calculation by Frank Krawczyk of LANSCE at LANL

Magnetic field of up to ~1400 Oe can be obtained at the sample port with $E_{peak}$~0.46 MV/m if it quenches at 2000 Oe at maximum magnetic field region.

Necessary cavity power is less than 1 W with $Q_0$~1E9

Samples will be placed at a high magnetic field region

# Tests at Cornell with 6-GHz Nb $TE_{011}$ Cavity

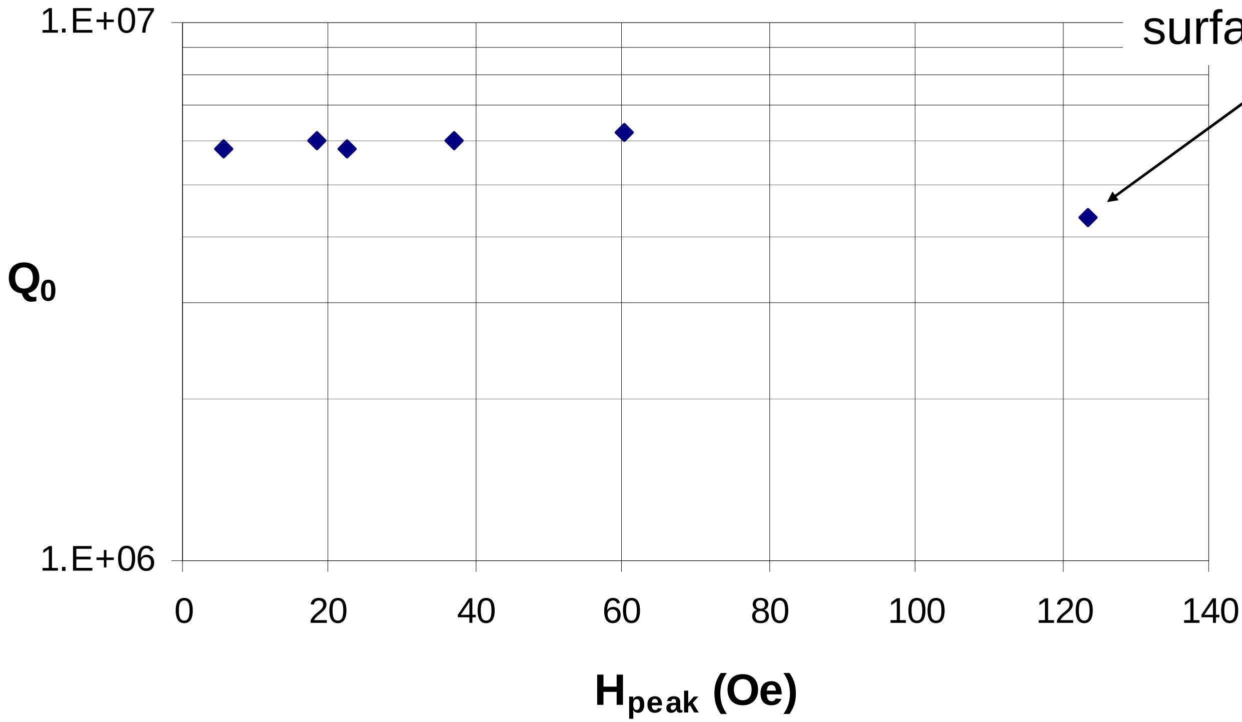



Measurement by Alexander Romanenko, Hasan Padamsee

At 4.2 K

**$Q_0$ vs $H_{peak}$ for 6 GHz $TE_{011}$-cavity with 400 nm $MgB_2$ film coated on Nb sample**

This might be due to surface heating

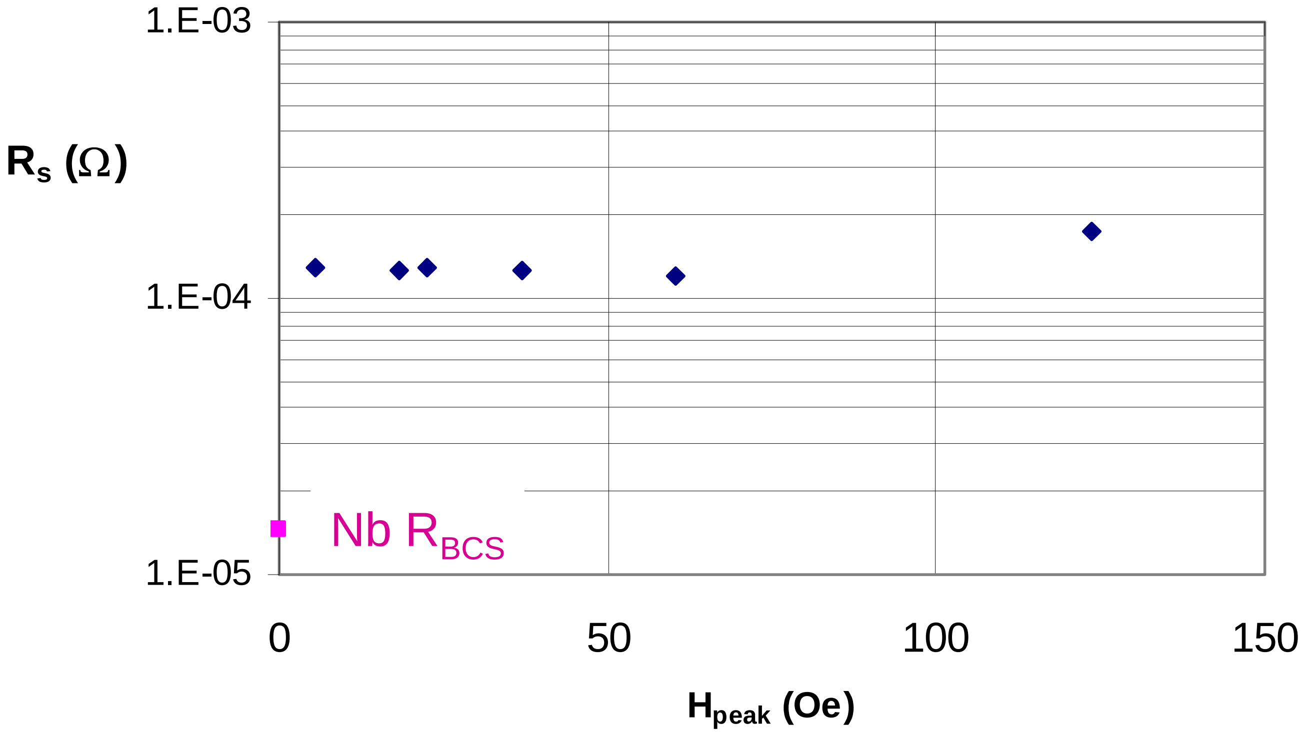



Limited by available power

Results at Cornell University

**$R_s$ vs $H_{peak}$ for $TE_{011}$-cavity with 400 nm $MgB_2$ film coated on Nb sample**

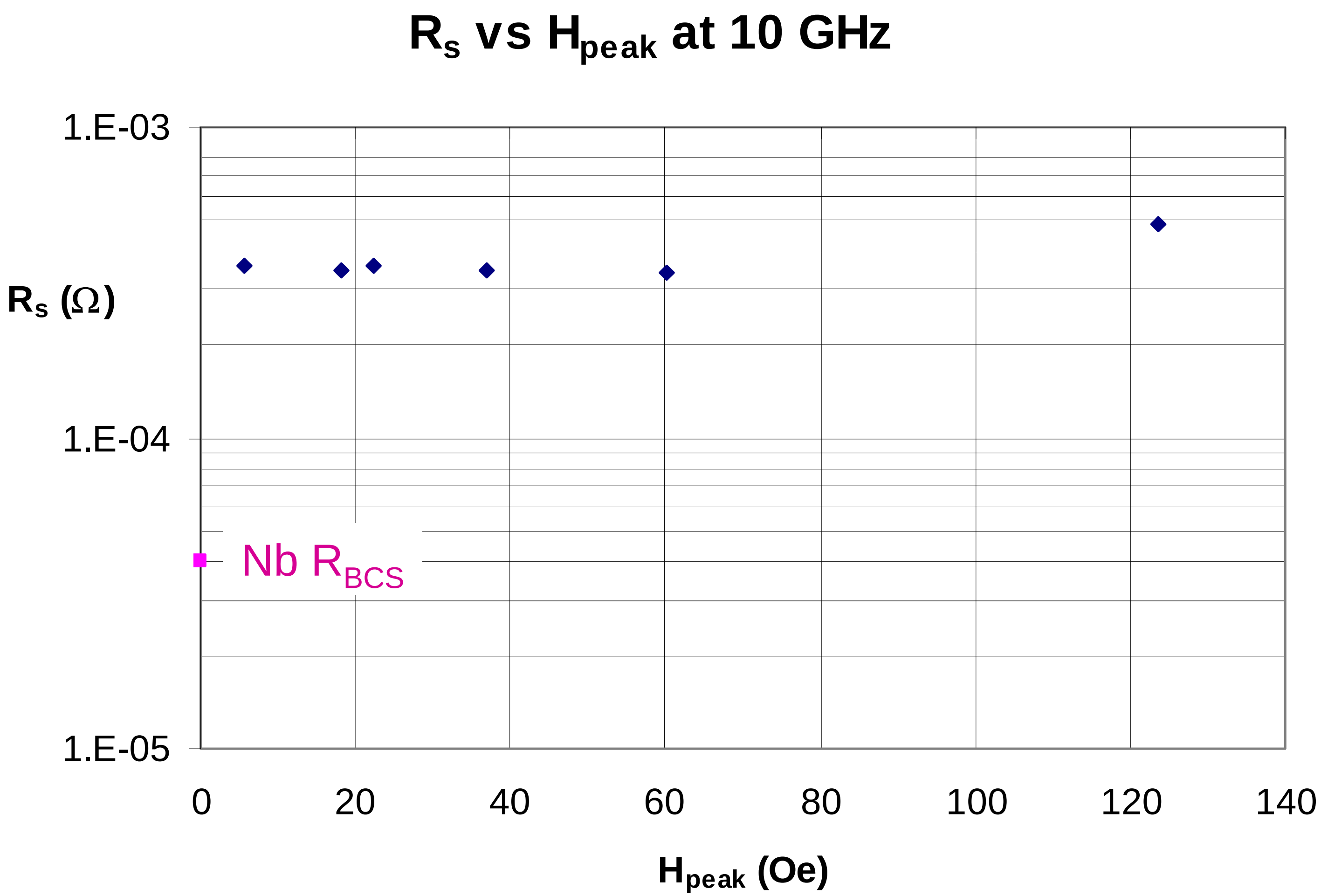
Results at Cornell University




$R_s$ is dominated by $MgB_2$ sample

At 6 GHz, $R_s$ of Nb is dominated by $R_{BCS}$ since $R_{res}$ is <10 n$\Omega$

At 6 GHz


$R_s$ vs $H_{peak}$ at 10 GHz
$R_s$ ($\Omega$)
1.E-03
1.E-04
1.E-05
Nb $R_{BCS}$
0
20
40
60
80
100
120
140
$H_{peak}$ (Oe)

# Summary

- Low-field data for $MgB_2$ films coated on sapphire have shown a RF surface resistance at 10 GHz lower than Nb at 4K.
- First magnetic field dependence test using a film coated on Nb showed no $Q_o$ degradation up to 60 Oe and ~28 % drop at ~120 Oe in $H_{peak}$ . The data at ~120 Oe might be due to surface heating. The measurement is limited by available power. Also, the film quality was not as good as the one coated on sapphire and may be due to the rougher substrate surface.

# Future Plans

- Magnetic field dependence tests with 760-MHz coaxial cavity at higher fields
- Try to reduce the $R_{res}$ of the film coated on Nb and get low-field and high-field $R_s$ data
- Pulse measurements on critical magnetic fields with a short pulse (<1 $\mu$s) to avoid thermal effect in collaboration with Ricky Campisi of SNS and Sami Tantawi of SLAC
- Develop a method to coat inner surface of SRF cavities and measure the cavity performance
  – Use existing LANL 3-GHz Nb cavities?
- Try to reduce $R_s$ of HIPped bulk $MgB_2$ and test samples at low- and high-magnetic fields
- Develop a method to coat $MgB_2$ film on copper